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Waste heat recovery using a thermoelectric power generation system in a biomass gasifier

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HIGHLIGHTS

- Set up the thermoelectric power generation system to recover waste heat from biomass gasifier.
- Bi_2Te_3 based material is suitable for choosing as a thermoelectric generator in the waste heat recovery temperature range of 473–633 K form gasifier.
- The maximum power density can reach 193.1 W/m^2 for waste heat recovery.

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ABSTRACT

The aim of this study is to investigate the use of waste heat that is recovered from a biomass gasifier. In the gasification process, the low heating value of biomass can be transferred to a high heating value for combustible gaseous fuel, a form that is widely used in industry and power plants. Conventionally, some of cleaning processes need to be conducted under higher operating temperatures that the low temperatures typically used to burn biomass. Therefore, the catalytic reactor was designed before installation the scrubber in the downdraft gasifier system to make effective use of the waste heat. The experimental result shows that the temperature of the gasifier outlet is about 623–773 K; dolomite is used for tar removal in the catalytic reactor. To further improve the use of waste heat, a thermoelectric generator is added to provide for the recovery of waste heat. The thermoelectric generator system is manufactured using a Bi_2Te_3 based material and is composed of eight thermoelectric modules on the surface of catalytic reactor. The measured surface temperature of the catalytic reactor is 473–633 K that is the correct temperature for Bi_2Te_3 as thermoelectric generator. The result shows that the maximum power output of the thermoelectric generator system is 6.1 W and thermoelectric generator power density is approximately 193.1 W/m^2.

1. Introduction

Governments worldwide are dealing with energy shortages; this serious problem causes everyone to actively seek alternative to fossil fuels. Therefore, gasification has been developed as a way to convert biomass to a higher heating value syngas. Three main types of gasifiers exist: fixed bed, moving bed and fluidized bed gasifiers based on fuel type and temperature. Downdraft gasifiers of a fixed bed type are regarded as a good solution to generating syngas with high heating value [1]. Many researchers have explored this technology. Jain et al. [2] used four open core throatless rice husk gasifiers to complete ten runs of experiments. Several factors including optimum equivalence ratio, optimum specific gasification rate, lower heating value and efficiency were determined. Yin et al. [3] introduced an empirical formula that can be used to determine the optimal diameter of a gasifier and various gasification parameters. A circulating fluidized bed (CFB) gasifier has also been applied to gasified rice husks to compare actual results with a mathematical model. Yoon et al. [4] gasified two different types of rice husks to study gasification results. Syngas produced from gasification were analyzed, compared and supplied to an engine to generate power. Ogi et al. [5] conducted experiments in an entrained-flow gasifier to gasify oil palm residues (empty fruit bunch). The relationship between the water–carbon and hydrogen–carbon monoxide ratios under different water and oxygen concentrations were discussed. Gasification results were also compared to a thermo-gravimetric analysis.

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Thermoelectric generators (TEG) have become popular devices because of their ability to transform a low-level heat source into higher power output unit. Three major theories can be used to describe their working principal, including the Seebeck, Peltier, and Thomson effects. The Seebeck effect theory states that two different but connected metals with different temperatures will cause an electromotive force between these materials. The Peltier effect is an inverse of the Seebeck effect, in that a temperature gradient may be produced from applying an electrical potential between two different connected metals. When electric current passes through heterogeneous conductors, and aside from generating irreversible Joule heat, the conductors will absorb or create a fixed amount of heat. This is called Thomson effect.

Many kinds of materials can be applied to a thermoelectric modulus. Different materials lead to different working temperature of TEG [6,7]. Therefore, many studies have focused on this topic. Cheng et al. [8] constructed a three-dimensional model that can be used to simulate the transient thermal condition of TEG. The TEG was simply separated into four regions, including semiconductor materials, hot junction and cold junction. It has been shown that current, heat loss and heat transfer coefficient strongly influence the coefficient of performance (COP). Gou et al. [9] established a steady-state dynamic model to predict behaviors of TEG with finned heat exchanger. The results showed that the heat dissipation rate on a cold junction has a strong effect on power output and fluctuation of the hot reservoir leads to variation of output power. Jang et al. [10,11] founded out that TEG modulus spacing has a great impact on the output power density. By using the finite difference and simplified conjugate-gradient methods, the optimized spacing and spreader thickness problems were solved. Montecucco et al. [12] applied a Simulink-Matlab program to simulate large-scale thermal and electrical dynamics of TEG. The results were also compared with an experiment to confirm accuracy and capability.

Because the TEG modulus converted heat to electrical power, it has many applications such as recovering heat from a car engine and boiler to make better use of waste heat produced from those types of equipment. Previous studies have shown that this method has been widely used with the heat generating equipment. Choi et al. [13] combined TEG with a car-seat system, installing an air conditioning system with a fan and ductwork to control the temperature on the warm side. A mathematical model was also created to predict the results. Chang et al. [14] established a thermal analogy network designed to predict the thermal condition of a TEG. When compared to a heat sink in an air-cooled system, a TEG has better performance under a low heat load. Champier et al. [15] combined a biomass cook stove with a TEG to recover waste heat and generate electric power. The optimal placement of the TEG on the stove was also investigated. Hsiao et al. [16] compared an exhaust pipe and radiator of automobile to find a better place to locate a TEG. A one dimensional thermal resistance model was applied to predict results. Zheng et al. [17,18] constructed a thermoelectric cogenerating system to generate power from a TEG and produce hot water simultaneously.

Ma et al. [19] applied an Umberto Life Cycle Assessment (LCA) model to investigate gasification of coal and petroleum coke, and evaluated the environmental impact from the process of gasification. Shie et al. [20] gasified rice straw in an attempt to provide a potential biofuel in Taiwan. The Energy Life Cycle Assessment (ELCA) model was used to simulate gasification conditions. Ma et al. [21] introduced Fire Dynamics Simulator (FDS) model to predict the temperature profile of a gasification system. Furthermore, a TEG modulus was also applied to study parameters such as output voltage and power generation. Hsu et al. [22] studied the effect of grin refinement to the ZT value of new thermoelectric material, with high temperature working conditions.

The aim of this study is to examine the use of waste heat that is recovered from a biomass gasifier. Also, the low heating value of biomass can be transferred to the high heating value of a combustible gaseous fuel during the gasification process. The experimental results show that the temperature of the gasifier outlet is about 623–773 K. To further improve the use of waste heat, the thermoelectric generators system (TEG) is attached to the surface of a catalytic reactor, which is used for cleaning (Fig. 1). Due to its high temperature, it can serve as a heat source of hot junction on the TEG. The measured surface temperature of a catalytic reactor is 473–633 K which is suitable for choosing Bi_2Te_3 as a

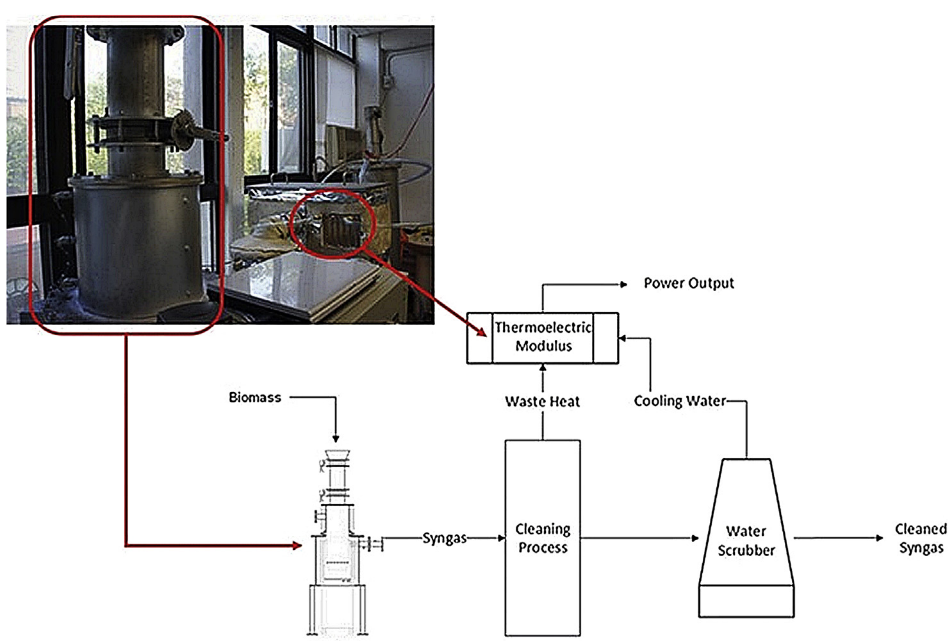

Fig. 1. Schematic diagram of the waste heat recovery system.

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thermoelectric generator. Also, the thermal efficiency of gasification and electrical properties of TEG are studied in this paper to evaluate the feasibility of using the device.

2. Experimental process

A previous study shows that a downdraft gasifier produces better quality gas and has lower tar content than updraft gasifier [1]. Some type of cleaning process is needed to allow the fuel to react under higher operating temperatures to have a higher quality of gas production. However, if a water scrubber is placed before the catalytic reactor, the temperature of syngas cannot be maintained for the cleaning process. Therefore, in this study the catalytic reactor is designed to be placed before scrubber in the downdraft gasifier system to make use of the waste heat more effectively.

2.1. Experimental apparatus

The gasifier system in this study shows the use of syngas via a catalytic reactor before the scrubber and investigates the waste heat recovery from a catalytic reactor with a TEG system. Fig. 1 shows a schematic diagram of the waste heat recovery system.

The TEG used in this study was manufactured by the Industrial Technology Research Institute. It includes a heating collector plate, cooling pipe and eight thermoelectric components which were made using a Bi_2Te_3 based material. Bi_2Te_3 has been widely applied for use in low temperature applications. The performance of a Bi_2Te_3 based material TEG is affected by the ZT value. The ZT value is affected by working temperature and manufacturing processes. Many studies have investigated the enhancement of the ZT value [23,24]. In this study, the maximum ZT value of Bi_2Te_3 was 0.67 at 353 K. Fig. 2 shows the experimental apparatus for the TEG system.

2.2. Fuel material

In Taiwan, Japanese cedar is used in construction, decoration and bridge building, etc.; however, only a small portion of Japanese cedar waste is currently being used as compost and the remainder is often burned as waste. In this study, the Japanese cedar waste material is used as fuel to test a downdraft gasifier. Table 1 shows the characteristics of Japanese cedar, showing that Japanese cedar has a high heating value (HHV) of approximately 21.1 MJ/kg and also has lower ash content. The air flow rate is controlled to change the equivalence ratio, and Table 2 shows the gasification conditions. Syngas composition at the exhaust of the gasifier was recorded every 15 min all during experimental.

2.3. Parameter definition

2.3.1. Equivalence ratio (ER), Φ

The equivalence ratio (ER) is defined as the actual AF ratio (air to fuel ratio) divided by the stoichiometric AF ratio, as shown in Eq. (1):

$$\Phi = \frac{\text{Actual Air to Fuel Ratio}}{\text{Stoichiometric Air to Fuel Ratio}} \tag{1}$$

2.3.2. Cold gas efficiency, CGE

The degree of cold gas efficiency (CGE) is an important characteristic that is valid for all gasification processes for any fuel and allows the comparison of the efficiency of various gasification processes. The cold gas efficiency is defined in Eq. (2):

$$\text{Cold Gas Efficiency} = \frac{\text{HHV}_{\text{gas}} \times \text{gas production rate}}{\text{HHV}_{\text{biomass}} \times \text{biomass feeding rate}} \times 100\% \tag{2}$$

2.3.3. Thermoelectric conversion efficiency, η

The thermoelectric conversion efficiency is defined in Eq. (3):

$$\eta = \frac{T_H - T_C}{T_H}\left[\frac{(1+ZT)^{0.5} - 1}{(1+ZT)^{0.5} + T_c/T_H}\right] \tag{3}$$

where T_H and T_C are the hot side and cold side temperatures of the thermoelectric module, respectively. ZT is a dimensionless figure of merit.

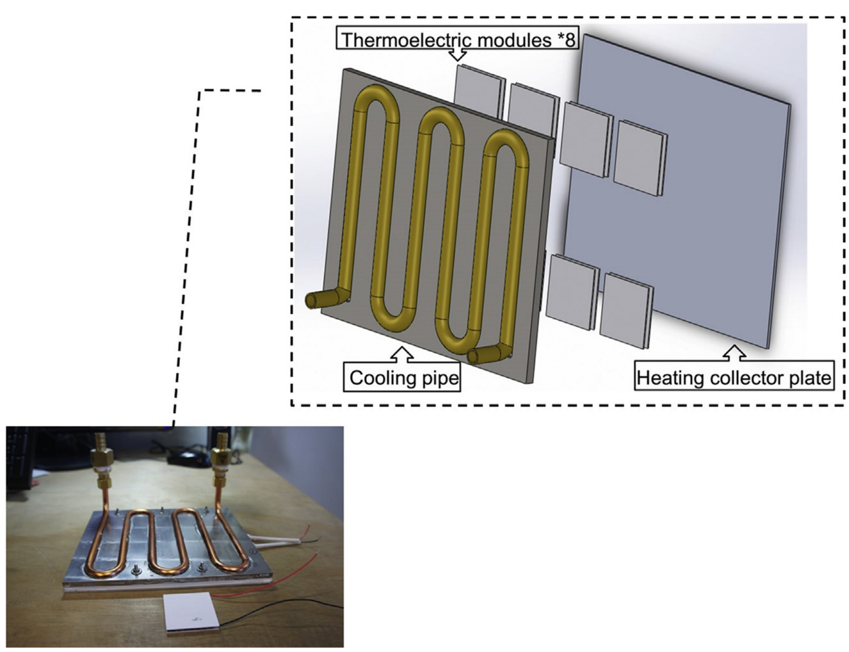

Fig. 2. The experimental apparatus for thermoelectric generators system.

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Table 1
Proximate and ultimate analysis of Japanese cedar.

Property	Japanese cedar
Proximate analysis (wt%; wet basis)	
Moisture	11.06
Volatile matter	80.85
Ash	0.73
Fixed carbon	7.35
Ultimate analysis (wt%)	
C	51.4
H	6.23
O	41.34
N	0.27
S	0.43
HHV (MJ/kg)	21.1

Table 2
Gasification conditions at different equivalence ratios.

Equivalence ratio (Φ)	Feeding rate (kg/h)	Air inlet (L/min)
0.2	1.8	31.79
0.3	1.8	47.68
0.4	1.8	63.57
0.5	1.8	79.47

2.3.4. Power density

The power density of TEG system is the ratio of power output (W) and area of TEG system (m^2). The power density is defined in Eq. (4):

$$\text{Power density} = \frac{\text{Power Output of TEG system}}{\text{Area of TEG system}} \tag{4}$$

3. Results and discussion

3.1. Gasification performance

The composition of syngas, which is produced from gasification experiments, was measured by a gas chromatograph (CHINA CHROMATOGRAPHY GC2000) with thermal conductivity detector. Fig. 3 shows the syngas composition produced from Japanese cedar gasification. The concentration trend of hydrogen is initially enhanced and then falls as ER increases. At $\Phi = 0.2$, the concentration of hydrogen is 8.41 vol% from Japanese cedar; these results may be caused by the lack of an air inlet. In addition, the maximum concentration of hydrogen obtained from the gasification of Japanese cedar is approximately 17.82 vol%. After the hydrogen concentration peaked, the concentration falls because of the excessive air inflow. Fig. 3 demonstrates that as ER increases, the concentration of carbon monoxide decreases. In addition, the concentration of carbon dioxide increases when ER increases, because when ER increases more oxygen is added to the reaction process. The maximum concentration of carbon monoxide from Japanese cedar gasification is approximately 20.4 vol%. Test results shows Japanese cedar had much more combustible gas, such as H_2 and CO.

The variation of the cold gas efficiency and higher heating value of syngas produced from Japanese cedar gasification with the ER is calculated by using the each heating value of gas composition. The main factors influencing the HHV are H_2, CO, and CH_4; their values are 12.75, 12.63, and 38.82 MJ/m^3, respectively. Cold gas efficiency increased up to $\Phi = 0.4$ and subsequently decreased. Furthermore, the syngas heating value has the similar tendency to result in an increase in cold gas efficiency performance. The maximum syngas heating value and cold gas efficiency of Japanese cedar calculates in this experiment were 5.01 MJ/m^3 and 76.26%, respectively. Therefore, optimum ER for gasification of Japanese cedar is found to be approximately 0.4.

3.2. Thermoelectric system performance

An experimental thermoelectric system was developed and built. The system is made of a Bi_2Te_3 material, with the dimensions of 200 mm × 160 mm × 12.64 mm with eight thermoelectric modules. And the performance of thermoelectric system was measured by an electronic load (FAST AUTO ELECTRONIC FA-2300), which including control current, control voltage and control power modes, with accuracy of current 1% and voltage 0.1%, respectively. Fig. 4 shows the experimental operation at different temperatures difference versus the open voltage, demonstrating that the open voltage has a clear positive correlation with the temperature difference; that is, the open voltage increases as the temperature difference increases. The maximum open voltage had been attained 59 V with operating temperature difference at 505 K.

The TEG system conversion efficiency was determined under hot side and cold side temperature as shown in Eq. (3). Fig. 5 shows

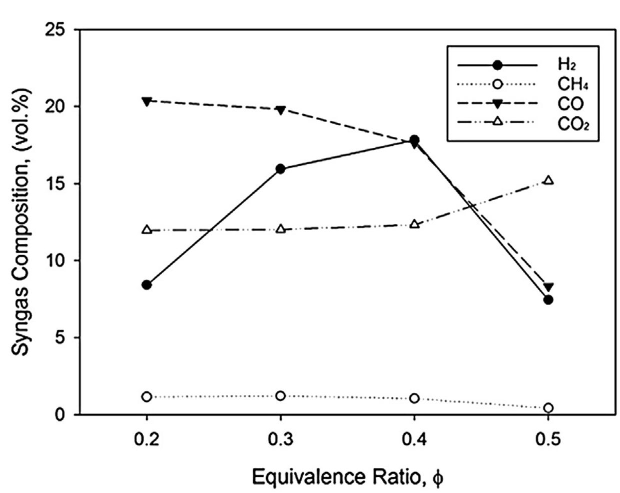

Fig. 3. Composition of syngas produced from Japanese cedar gasification.

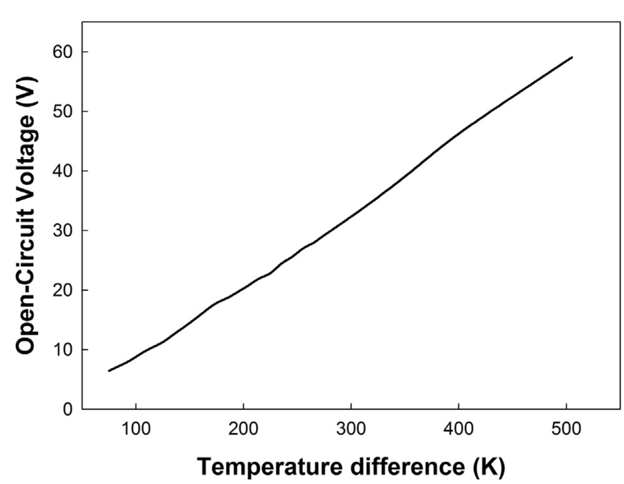

Fig. 4. Open voltage output with different operating temperature differences.

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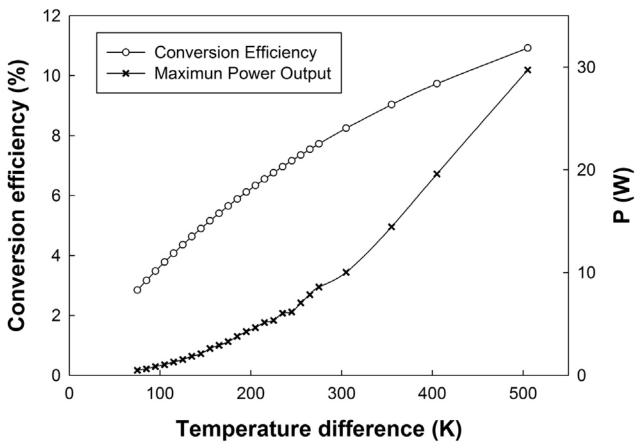

Fig. 5. Thermoelectric conversion efficiency and maximum power output at different temperature differences.

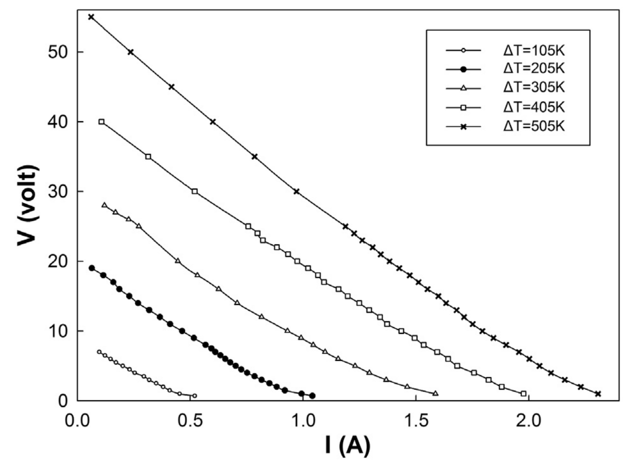

Fig. 7. *V*–*I* curves at different temperature differences.

thermoelectric conversion efficiency and maximum power output at different temperature difference; obviously, the conversion efficiency and maximum power output increase as the temperature difference increases. The results indicate that the theoretical trend of the conversion efficiency agrees fairly well with the experimental trend of power output. In this study, the highest and lowest conversion efficiencies are approximately 10.9% and 2.8% with a 505 K and 75 K temperature difference, respectively.

Fig. 6 displays the power and voltage profiles vs. current for different values of T_H and T_C at the same temperature difference. The results show that the difference of T_H and T_C influence power output more strongly than the voltage. From these results, one may deduce that at the same temperature difference the higher T_H will attain a higher power output, and that the T_H may not significantly influence the voltage.

Figs. 7 and 8 demonstrate the voltage–current (*V*–*I*) and power–current (*P*–*I*) curves, respectively. In Fig. 7, it is evident that current increases when the voltage decreases, but the voltage and current clearly increase with increasing temperature difference. Fig. 8 demonstrates that as the temperature difference increases, power output gradually rises to the maximum value; this shows the maximum power output can reach 1 W, 4.6 W, 10 W, 19.6 W and 29.7 W at a temperature difference of 105 K, 205 K, 305 K, 405 K and 505 K, respectively. The results demonstrate that the range of operating temperature differences of 105–505 K all have good electrical performances.

3.3. Waste heat recovery

This study uses dolomite as a catalyst to cracking tar, the temperature contour on a catalytic reactor's surface during the process of gasification of Japanese cedar is around 473–633 K, and it matches the desired operating temperature for a thermoelectric generation system. Fig. 9 demonstrates the power and power density from the thermoelectric generation system with a gasifier. The experimental data was recorded every 15 min. At the first hour with a low equivalence ratio and oxygen shortage, incomplete combustion occurred that lead to a lower power output. In addition, as the equivalence ratio increased the power output increased, because the combustion tended to be complete and had a higher waste heat temperature. The power output in this study is approximately 2.9–6.1 W, and the power density is approximately 91.5–193.1 W/m^2.

In this study, biomass gasification and thermoelectric generation are two independent systems, the cold gas efficiency of the gasifier is approximately 76.26%. The waste heat recover amount from gasifier is dependent on flue gas temperature and the size of thermoelectric generator. Under these circumstances, the thermoelectric conversion efficiency of the waste heat recover from the gasifier is approximately 5.4%–7.16%.

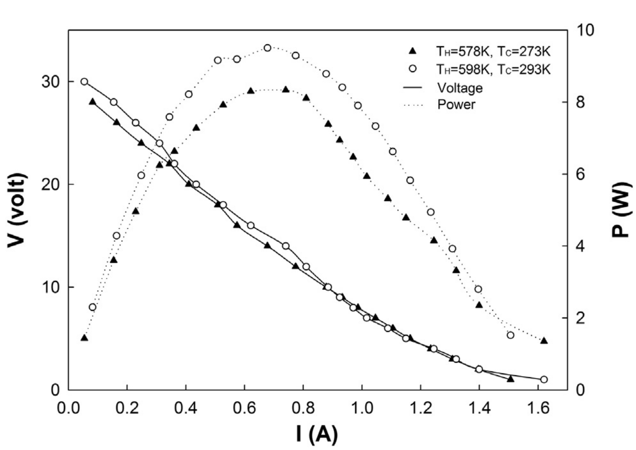

Fig. 6. *P*–*I* and *V*–*I* curves for different values of T_H and T_C when at the same temperature difference.

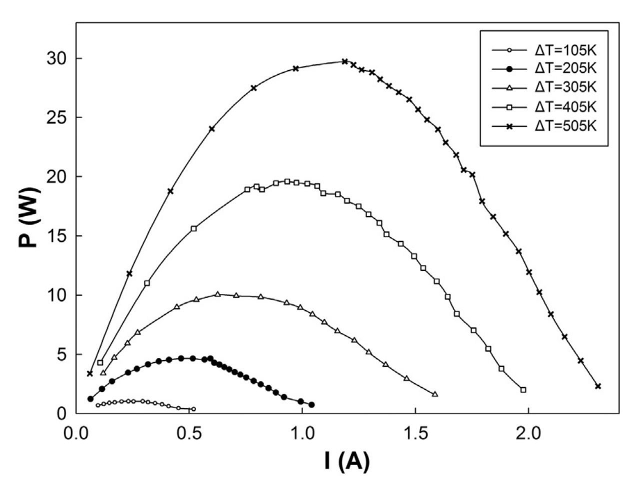

Fig. 8. *P*–*I* curves at different temperature differences.

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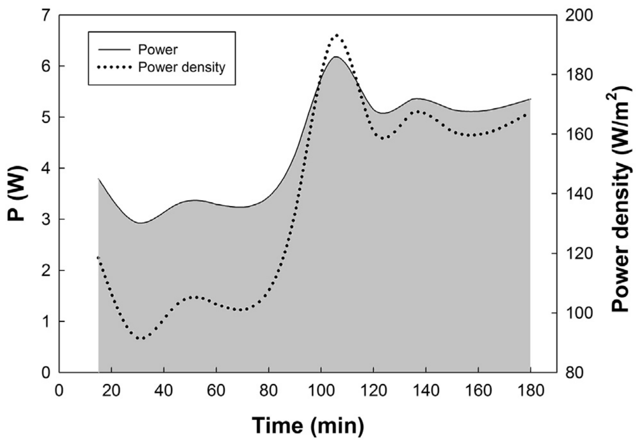

Fig. 9. Power output and power density from gasifier waste heat recovery.

4. Conclusions

This study analyzed the gasification of waste biomass and the performance of a thermoelectric generation system, which was used to improve the use of waste heat in a downdraft gasifier. The major conclusions follow:

1. The maximum concentration of hydrogen is approximately 17.82 vol% during Japanese cedar gasification. Test results shows Japanese cedar had much more combustible gas, but higher amounts of CO_2 were produced. In addition, the optimal ER for the Japanese cedar was found ($\Phi = 0.4$), it can allow a syngas heating value and cold gas efficiency of 5.01 MJ/m^3 and 76.26%, respectively.
2. The operating temperature difference for a thermoelectric generation system is in the range of 105–505 K, and it can be obtained with a maximum open voltage of 59 V and a maximum power output of 29.7 W at a 505 K temperature difference.
3. The maximum and minimum conversion efficiencies of the thermoelectric generation system to generate power is approximately 10.9% at a 505 K temperature difference and approximately 2.8% at a 75 K temperature difference.
4. At the same temperature difference, a higher T_H will result in higher power output, and the T_H may not influence the voltage significantly.
5. The surface temperature of the catalytic reactor is approximately 473–633 K. The performance of the thermoelectric generation system which is used for waste heat recovery shows the maximum power output is approximately 6.1 W and it has a power density is approximately 193.1 W/m^2.

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